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# A robust solution for hesitate phenomenon in pick up process of aerospace electromagnetic relay

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Robust design

**Abstract** As for aerospace electromagnetic relay (AEMR) which is of small batches and having difficulty in automatic production, the uncertainty phenomenon is remarkable due to excessive manual work involved in the assembly and adjustment processes. This kind of uncertainty may increase the coil voltage difference (CVD) caused by hesitate phenomenon in the pick up process of AEMR. Taking a certain type of AEMR for example, the CVD problem in the actual producing process has been studied in this paper. The primary cause of this issue, two-steps of armature motion (namely hesitate phenomenon) in the pick up process, has been found by analyzing the matching characteristics of electromagnetic and mechanical torques of AEMR. Through the optimization of the matching characteristics, the two-steps of armature motion problem is solved by robust design of the return reed which is a key part of AEMR. The validity of this research has been proved by the comparison of characteristics of AEMR before and after the optimization.

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## 1. Introduction

Aerospace electromagnetic relay (AEMR) is a type of high-performance relays which is sealed by a metal shell using a fusion welding method. AEMR has advantages of high conversion depth, multi-channel synchronous control, and strong ability of anti-jamming capability, which cannot be replaced by solid electronic devices. Therefore, it has played important roles in insulation, signal transmission, and power switching of

high-reliability-requirement situations including aerospace, national defense, etc.

The production batch of AEMR is relatively small due to special application requirements, and together with the compact structures, an automatic process (especially the assembling process) would be in great difficulty. Excessive manual work involved in the production process results in remarkable uncertainty of product characteristics. Taking the 1/2 crystal cover AEMR (21 mm × 11 mm × 11.5 mm) discussed in this paper for an example, over half of the products in the assembling process have the problem of high coil voltage difference (CVD) and large dispersion. The CVD means the value difference of two coil voltages corresponding to the different action time of two unsymmetrical transition contacts during the slow increment of the coil voltage. The phenomenon occurs mainly in the assembling process. If the voltage difference is over a certain value, the AEMR is proved to have defects. High

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CVD may result in serious arc erosion while relays operate with load, and would affect the performance of the whole batch of AEMR greatly.

For the uncertainty problem of electromagnetic relay (EMR), Lu and Jin<sup>1</sup> took pick up voltage as a random variable, and established a calculation model of unqualified probability of EMR. Su and Lu<sup>2</sup> proposed a pick up reliability theory of EMR, set the minimum of operating voltage as “strength” and tested pick up voltage as “stress”, and then built a mathematic model that could be used in electromagnetic system optimization design.<sup>3</sup> To solve the size uncertainty problem of EMR caused by manufacturing, a “stress-strength interference” theory was introduced into tolerance design in Ref. <sup>4</sup>, and a method for tolerance design of EMR based on matching characteristics of electromagnetic and mechanical forces was proposed. To improve the dynamic fusion welding phenomenon of automobile relay in the process of breaking excitation current in motors, a robust design with internal-external orthogonal experiment was adopted by taking over-travel, contact material, coil voltage, and coil suppression component as controllable factors, while contact surface topography and breaking current as noise factors.<sup>5</sup> Yang<sup>6</sup> took stress relaxation, contact press, and reed size as random variables, and studied the reliability optimization of reed in constant section and arbitrary shape using a simplex method. Weng et al.<sup>7</sup> adopted the Taguchi method to optimize the electromagnetic system of a linear antenna array.

For EMR, scholars did a lot of research works in the fields of contact arc<sup>8–10</sup> and optimization design,<sup>11,12</sup> but the uncertainty problem of EMR caused by machining dispersion attracted less attention to. The CVD problem researched in this paper has not been reported till now.

Taking the 1/2 crystal cover AEMR for example, this paper studies the CVD problem and its dispersion by analyzing matching characteristics of electromagnetic and mechanical torques. The results prove that the primary cause of this issue is a two-steps phenomenon of armature motion in the pick up process of AEMR, which is caused by the bad matching characteristics of electromagnetic and mechanical torques. Based on the analysis, the return reed is recognized as a key part of matching characteristics optimization and two-steps-problem solutions. Then an orthogonal experiment is adopted to optimize the parameters of the return reed. The simulation results and products testing outcome before and after the optimization also have been compared.

## 2. Analysis of matching characteristics

Fig. 1 shows the inner structure of a certain type of AEMR studied in this paper, which has a nominal operating voltage of DC 28 V and contains two sets of transition contacts. Ideally, two transition contacts should be completely symmetrical, which makes the mechanical torque curve consist of four parts, as shown in Fig. 2.

Segment “a” is provided by the return reed; segment “b” by combination of the return reed, the normally open (NO) fixed reed, and the moving reed; segment “c” by combination of the return reed and the moving reed; segment “d” by combination of the return reed, the moving reed, and the normally closed (NC) fixed reed.

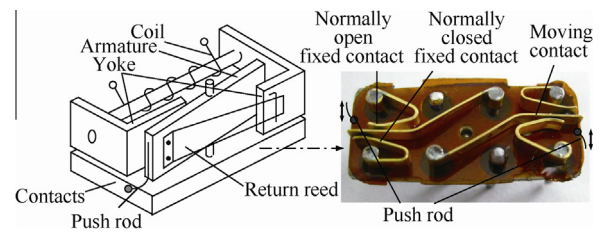


Fig. 1 The 1/2 crystal cover AEMR.

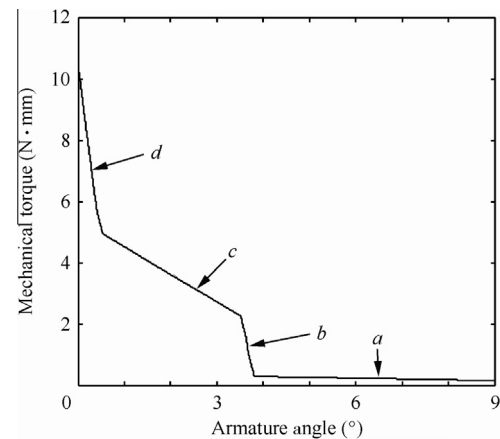


Fig. 2 Mechanical torque curve.

For a relay with this mechanical structure, the asymmetry of two sets of transition contacts is the essential reason of the CVD problem, but generally the influence of this kind of asymmetry is not very significant. It is considered that the two-step phenomenon of armature motion in the pick up process has enlarged the influence of asymmetry on the CVD.

In order to verify conjecture mentioned above, a simulation model of AEMR is established (Fig. 3), and according to the real adjustment process of this AEMR, the matching characteristics of electromagnetic and mechanical torques under certain coil voltages are simulated.

During simulation, the coil voltage increases slowly from 0 V. Meanwhile, the armature angular velocity is monitored to stop the increment of the coil voltage when the armature begins to rotate. The simulation results are shown in Fig. 4. The electromagnetic torque is lower than the mechanical torque at the initial time. The armature keeps static until the coil voltage increases to 9.1 V, and then the electromagnetic torque is higher than the mechanical torque. The armature begins to rotate, and the coil voltage keeps constant. Because of the high gradient of segment “b” in the mechanical curve (shown in Fig. 2), the electromagnetic torque cannot overcome the mechanical torque, as shown in Fig. 4(b). Thus, the armature stops rotating. Then the coil voltage is increased gradually from 9.1 V. It is found that when the coil voltage increases to 15.9 V, the electromagnetic torque exceeds mechanical torque once again, and the armature continues to rotate until moving to the end position.

In the pick up process, with the coil voltage increasing slowly, the armature begins to rotate but cannot move to the end position until the coil voltage increases to the value where

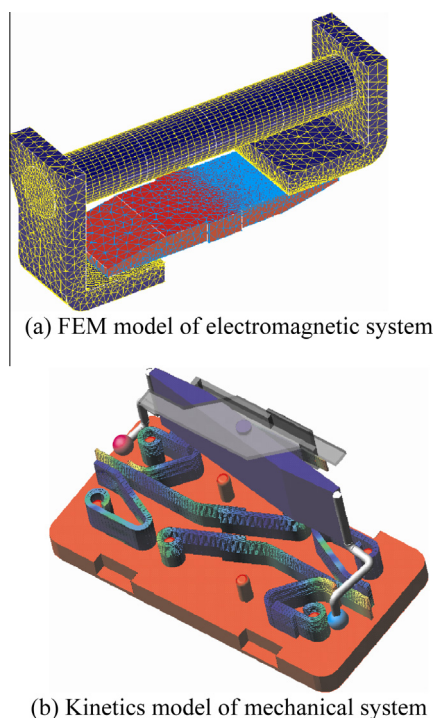


Fig. 3 Simulation model of AEMR.

electromagnetic torque exceeds the mechanical torque once again. This phenomenon is defined as the two-steps of armature motion in the pick up process.

As for a relay of symmetrical type including two sets of transition contacts, the two-steps of armature motion phenomenon in an assembling process can be described by the value difference of two coil voltages (CVD) corresponding to the different breaking time of two sets of transition contacts, while the contact pressure decreases to 0 N, as shown in Fig. 4(a). Generally, the allowable range of the CVD is within 1–2 V. Fine adjustment is acceptable in a manual assembling process. However, when the CVD exceeds the threshold value too much due to unreasonable matching characteristics of electromagnetic and mechanical torques, for example, the CVD of this AEMR is 2.7 V according to Fig. 4(a), the parameters and positions of all reeds in the mechanical system need to be adjusted repeatedly and drastically by hand to meet the adjustment requirements. On one hand, the characteristics of the theoretically designed relay would be destroyed; on the other hand, because of uncontrollable features of manual work, the consistency of batch products would be very low.

The above simulation results have proved the rationality of the existence of the CVD. They also indicate that the elimination of two-steps of armature motion phenomenon by optimization of matching characteristics can effectively eliminate the CVD problem.

### 3. Determination of optimization objective and optimization scheme

In order to make the relay operate without hesitation (in one step), the intersecting part of electromagnetic and mechanical curves in matching characteristics should be reduced. A decrease of the mechanical torque and an increase of the electro-

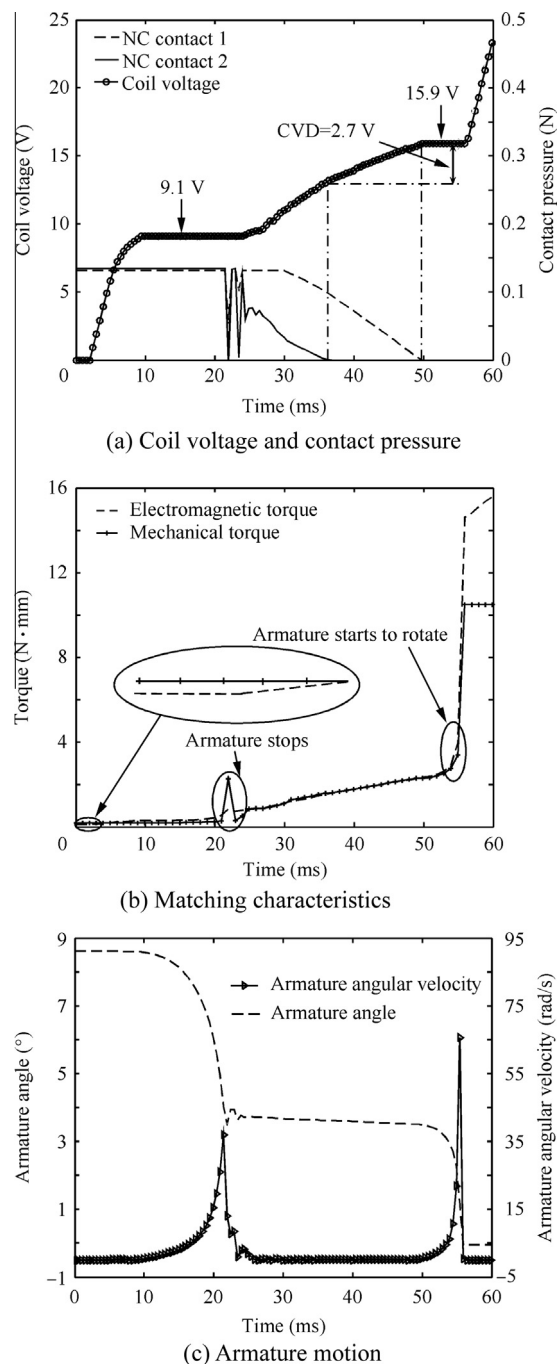


Fig. 4 Simulation results in assembling process.

magnetic torque are both the means to realize the requirements mentioned above. However, the mechanical torque is determined by the load, so its decrease would go against the arc extinguish during the breaking process of contacts. Meanwhile, an increase of the electromagnetic torque would raise the power consumption. Therefore, these two methods should not be adopted arbitrarily in order to achieve the purpose of relay operation in one step.

As mentioned before, the assembly and adjustment processes are the main factors which cause the inconsistency of relays. Thus, for the AEMR studied in this paper which has been of batch production, the optimization study of the assembly

and adjustment processes is the key point. The amount of parts that need to be modified and the change of the parts' performance should be as small as possible in the process of optimization design.

Aiming at the CVD phenomenon or two-steps of armature motion in the pick up process, return reed, magnetic gap of electromagnetic system, moving reed, and NC fixed reed are the parts adjusted with most times and largest range in actual adjustment. Actuation voltage of the armature can indicate the adjustment extent of the return reed. Table 1 indicates the actuation voltage of the armature before and after the adjustment of the return reed in a batch production. When the actuation voltage is too low, workers need to make some plastic deformation adjustment to the return reed, until the voltage meets the requirement (i.e., relay can pick up in one step). In addition, Table 1 also shows that a relatively big adjustment has been made during the return reed adjustment process, which would increase the difficulties of manual adjustment and cannot ensure the consistency of products. On the other hand, excessive adjustment even causes plastic deformation to some return reeds during the adjustment, which would make characteristics of the products unstable, especially that the consistency of products would become even worse after the process of temperature aging and mechanical aging.

According to the matching characteristics of electromagnetic and mechanical torques, armature actuation voltage would raise when the force of the return reed is increased. Therefore, the electromagnetic torque increases more greatly than before when the armature rotates to the segment “b” with a high gradient (shown in Fig. 2), which would help relays close in one step, as shown in Fig. 5. In addition, the segment “a” in the mechanical curve has a very low gradient, which only affects the armature actuation voltage and has little influence on the pickup and release voltages. It indicates that the return reed has a high independence in optimization, which makes it difficult to cause change of characteristics in other parts of the relay. Therefore, the improvement of the return reed is determined as the main optimization scheme to optimize the matching characteristics in this paper.

Simulation results indicate that when the armature actuation voltage is raised up to 15 V by increasing the return reed force, the relay can pick up in one step which is illustrated in Fig. 6. At this time the pickup voltage is also 15 V.

Here the increase of the force of the return reed is accomplished by enlarging the tip side offset (Fig. 7). However, a too large offset value would lead to instability of a relay's performance, especially after roast treatment. Therefore, it is

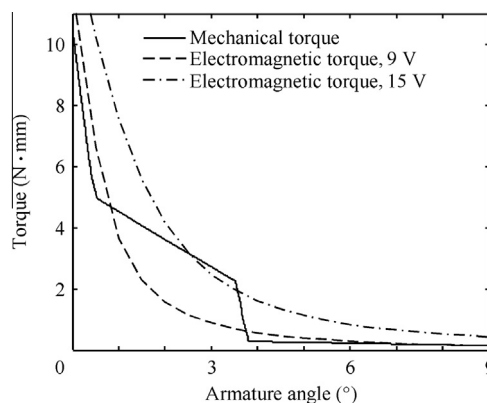
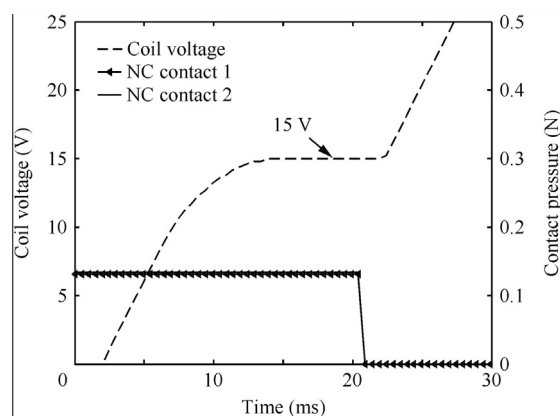
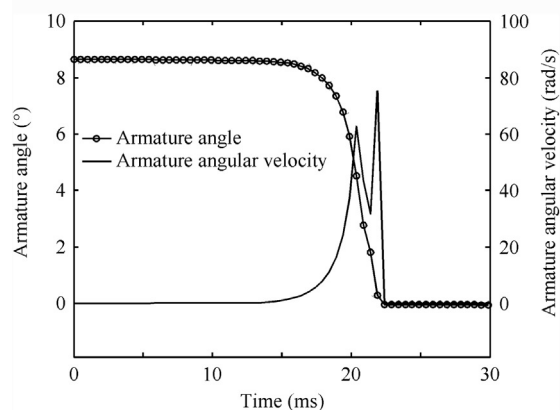


Fig. 5 Static matching characteristics of AEMR.



(a) Coil voltage and contact pressure



(b) Armature motion

Fig. 6 Simulation results after increase of return reed force.

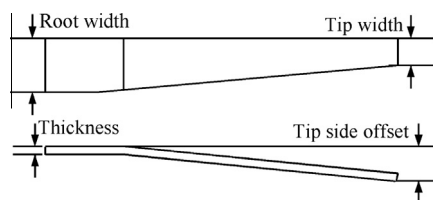


Fig. 7 Main design parameters of return reed.

**Table 1** Testing data of armature actuation voltage in adjustment process.

No.	Before adjustment of return reed (V)	After adjustment of return reed (V)
1	9.5	16.0
2	8.8	16.2
3	8.2	16.3
4	8.2	17.2
5	9.0	17.4

Note: Nos. 1–5 represent five different relays in the same batch, whose serial numbers are defined as 1–5.



necessary to take all parameters of the return reed into account during optimization.

#### 4. Optimization of return reed parameters

After determining the return reed as a key part and raising the armature actuation voltage from 9.1 up to 15 V as the optimization objective, the parameters of the return reed need to be optimized. The main design parameters of the return reed are thickness, root width, tip width, tip side offset, and material properties.

The orthogonal experiment design method is adopted to analyze the influence of the design parameters (Table 2) on the return reed force, through the variance analysis of sensitivity. Here  $L_82^7$  orthogonal table is chosen for experiment arrangement, i.e., eight experiments would be done. Experimental design and analysis results of sensitivity are shown in Table 2.

According to the experimental results, it is concluded that the thickness has a very significant influence on the return reed force; the influence of the tip side offset, root width, and material properties are obvious; and the tip width is minimum. Therefore, the thickness, tip side offset, and root width are determined to be the key parameters to optimize the return reed. The optimization order of the parameters is also determined according to each one's sensitivity. The change of the material properties are not considered in the optimization process.

According to the analysis results in Section 3, the optimization goal of the return reed is to ensure the armature actuation voltage is 15 V and the force of return reed should reach a certain value (here this value is 0.4920208 N·mm, and can be calculated by FLUX software). After finding out the significant factors by the orthogonal experiment, the optimization design can be done with the try-and-error method, and the partial optimization process of the key parameters is shown in Table 3. In the table, the "error" means the difference between 0.4920208 N·mm and the force of the return reed under different combinations of factor levels.

Eventually, optimization values of the return reed parameters are determined that the thickness is 0.12 mm, the tip side offset is 1.3 mm, and the root width is 1.6 mm.

#### 5. Verification of the optimization scheme

##### 5.1. Dynamic characteristics during adjustment process

Firstly, the dynamic characteristics of the adjusting process after the return reed optimization are analyzed. As shown in Fig. 8, the armature actuation voltage is 15 V, and the armature

**Table 3** Determination process of key parameters.

No.	Thickness (mm)	Tip side offset (mm)	Root width (mm)	Error (%)
1	0.13	1.4	2.0	5.116
2	0.12	1.4	2.0	3.546
3	0.12	1.3	2.0	2.067
4	0.11	1.3	2.0	1.103
5	0.12	1.3	1.8	0.884
6	0.12	1.2	1.8	0.717
7	0.12	1.3	1.6	0.546

motion in the pick up process completes in one step, i.e., the pickup voltage is 15 V and the CVD is 0 V. Comparing the characteristics of AEMR before and after the return reed optimization, it can be found that although the return reed force is increased, the pickup voltage is reduced from 15.9 to 15 V. It is because the armature would continue to move due to the inertia even when the electromagnetic torque is less than the mechanical torque, as shown in Fig. 8(c). The electromagnetic torque would continue to increase along with the decrease of the armature angle and then overcome the mechanical torque to pick up in one step, as shown in Fig. 8(b).

##### 5.2. Dynamic characteristics during operating

Dynamic characteristics of the operating process before and after the return reed optimization are also analyzed, as shown in Fig. 9.

After optimizing the return reed, the breaking moment of the NC contacts and the colliding moment of the NO contacts are lagged during the pick up process, but the change value of the speed is very small. It indicates that the change of the return reed force only affects the armature actuation voltage, but has little influence on the contact velocity and the armature angular velocity. As the electromagnetic torque grows continuously during the pick up process, it is inevitable that the increase of the initial mechanical torque would cause a hysteretic effect on the armature actuation time.

In the release process, the armature actuation time is nearly invariable, and the velocity change value is very small. The quantitative changes of the velocities in the NC and NO contacts are shown in Table 4.

##### 5.3. Actual product certification

Four products have been adjusted using the optimized return reed in actual production. The test results are shown in Table 5, which indicate that:

**Table 2** Experimental design and sensitivity.

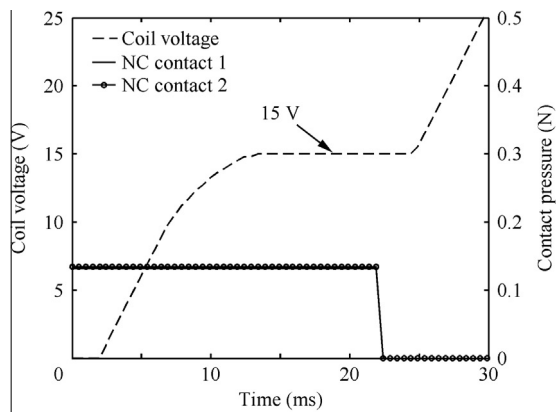
Factor level	Thickness (mm)	Root width (mm)	Tip width (mm)	Tip side offset (mm)	Material properties
1	0.10	1.5	1.3	1.0	Stainless steel
2	0.15	2.1	1.6	1.6	Beryllium bronze
Sensitivity	***	**	*	**	**

Note:

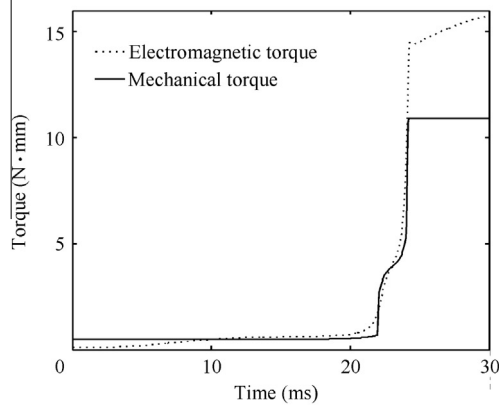
\* Means non-significant.

\*\* Means significant.

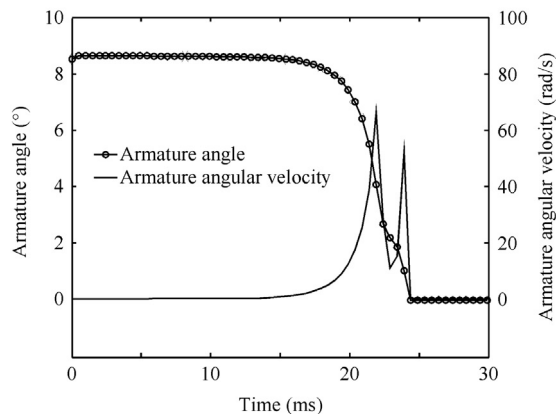
\*\*\* Means very significant.



(a) Coil voltage and contact pressure after optimization



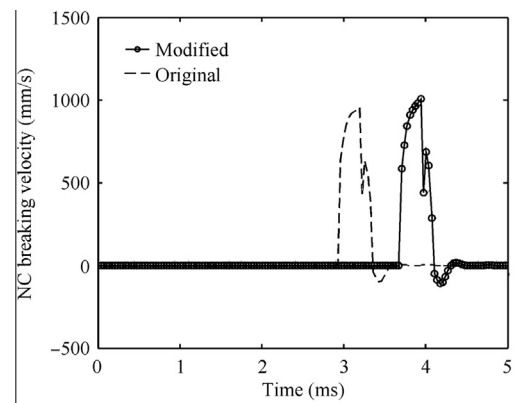
(b) Matching characteristics



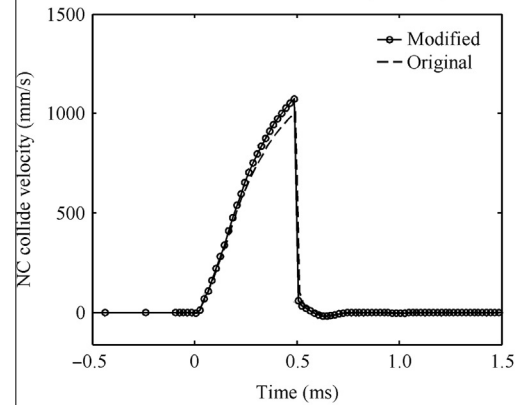
(c) Armature motion

**Fig. 8** Simulation results during adjustment process.

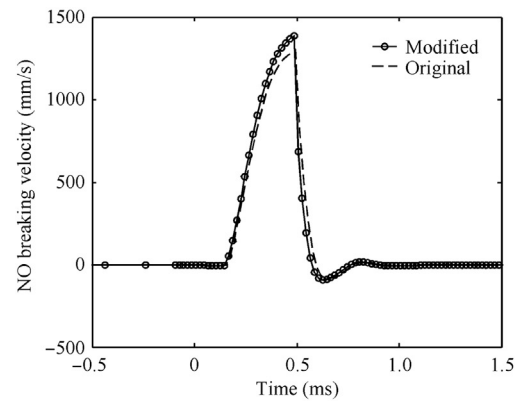
- (1) The first and second products have excellent behavior. The return reeds can make them operate in one step without adjustment (i.e., the CVD is 0 V), which would help ensure the consistency of batch products and improve the assembly efficiency.
- (2) The CVD of the third product is relatively larger. Though the CVD can be controlled by the adjustment of the return reed, the pickup voltage is a little higher than the requirement.
- (3) Before adjusting the return reed, the fourth product can operate in one step, but has a very high pick up voltage.



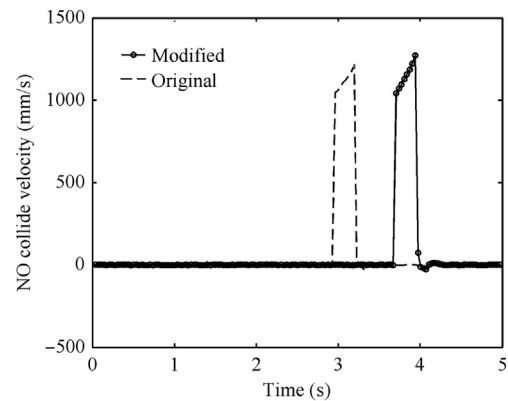
(a) NC contacts breaking velocity



(b) NC contacts colliding velocity



(c) NO contacts breaking velocity



(d) NO contacts colliding velocity

**Fig. 9** Simulation results during operating process.

**Table 4** Quantitative change of contact velocity (Unit: mm/s).

Pick up process	NC contacts breaking		NO contacts colliding	
Original	11.34	11.91	1228.28	1174.99
Modified	11.82	12.18	1297.65	1246.78
Change	4.24%	2.26%	5.65%	6.11%
Release process	NC contacts colliding		NO contacts breaking	
Original	1022.67	1019.17	3.32	2.91
Modified	1082.22	1075.99	3.58	3.00
Change	5.82%	5.58%	7.86%	3.07%

Note: the breaking velocity in the table means initial breaking velocity.

**Table 5** Product certification test data.

No.	Armature actuation voltage (V)	Coil voltage when contact 1 breaks (V)	Coil voltage when contact 2 breaks (V)	CVD (V)	Pick up voltage (V)	Release voltage (V)
<i>Before return reed adjustment</i>						
1	15.5	15.5	15.5	0	15.5	4.2
2	16.5	16.5	16.5	0	16.5	5.0
3	16.8	16.8	17.7	0.9	17.7	4.8
4	17.8	17.8	17.8	0	17.8	4.2
<i>After return reed adjustment</i>						
1	—	—	—	—	—	—
2	—	—	—	—	—	—
3	17.5	17.5	18.0	0.5	18.0	5.0
4	14.5	14.5	15.0	0.5	15.0	4.0

Note: for this AEMR, CVD must be less than 0.5 V. Pick up voltage had better less than 17 V.

Through adjusting the return reed, the armature actuation voltage is decreased and can meet the requirement.

## 6. Conclusions

As for the AEMR which is of small batches and having excessive manual work involved in the production process, the matching characteristics of electromagnetic and mechanical torques are very important for the elimination of uncertainty in the assembling process. Taking a certain type of AEMR for example, the problem of the CVD over an allowable value is studied in this paper by analyzing the matching characteristics of electromagnetic and mechanical torques, using virtual prototype technology. The simulation results prove that the two-steps phenomenon (namely hesitate phenomenon) of armature motion in the AEMR pick up process is the primary cause of voltage difference issues. Combining with the consideration of actual assembly and adjustment processes, the return reed is determined as a key part to solve the two-steps problem. Then a robust design method is used to optimize the key parameters of the return reed, such as thickness, tip side offset, and root width. After the optimization, the armature actuation voltage is increased from 9.1 to 15 V, which makes the matching characteristics of the AEMR more rational, so as to eliminate the two-steps phenomenon and the CVD problem.

Furthermore, the optimization of the return reed has been verified having little effect on the AEMR dynamic characteristics during the operation. It means that the optimization would

not make any negative influence on other performances of the relay.

By analyzing the matching characteristics of electromagnetic and mechanical forces, this paper proposes a simulation-based robust solution for AEMR. This method is universal and can be used to solve various problems caused by unreasonable design of relays. The method is not only suitable for AEMR with small batches, but also very important to normal switch products.

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